

PULSED EDDY-CURRENT CRACK-CHARACTERIZATION EXPERIMENTS

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INTRODUCTION

In the pulsed eddy-current (PEC) method of flaw detection, repetitive pulses of current in a transmitter coil are used to excite eddy currents in the test specimen. A separate receiver is excited by the transmitted and reflected fields, and variations in the receiver response are used to locate and characterize material variations of interest.

In contrast to conventional continuous-wave eddy-current examination, this approach is inherently broadband, thus offering at least the possibility of obtaining more information with one excitation waveform. For example, single-frequency eddy current has at most two variables, phase and amplitude or an equivalent set, that can vary and be measured compared to phase and amplitude as a function of frequency in the spectrum of a PEC receiver. In addition, PEC testing has time-domain information readily available; that is, the pulse and each frequency band within it appear at different times after traveling through the examination material. This feature occurs because the propagation velocity of electromagnetic fields in conducting material is a function of frequency; therefore, it is natural to consider information extraction in the time domain rather than the frequency domain.

Although the PEC technique has existed for some time, it has not found widespread application. Historically, most PEC approaches have attempted to use only a small part of the information available. One approach has been to simply measure the peak amplitude from a differential receiver coil [1]; discontinuity in the test material is indicated when the amplitude varies. Other approaches are based on the observation that certain points exist in the curve of output response to an induced pulse that do not change significantly when one variable, such as lift-off, is changed, but do change significantly in the presence of a defect. These points were explained by Waidelich [2]. Other suggested methods have involved sampling the received signal at several different points in time. The amplitudes thus obtained can then be parametrically combined in order to minimize the effect of variations of features not of interest and to maximize the signal due to features of interest [3, 4, 5]. This approach is motivated by a desire to obtain available depth sensitivity similar to multifrequency eddy-current testing, and it takes advantage of the fact that the frequency spectrum varies as a function of time in the received pulse.

The work described here is concerned with developing a time-domain approach to maximize the information availability and time-domain structure achievable with PEC testing. The purpose is to investigate the possibility of using the information to determine the depth of surface-breaking flaws. The materials of interest are titanium and other low-conductivity alloys used in rotating components of turbojet engines. Probes, pulse characteristics, and signal processing have been designed for this purpose.

PHYSICAL MODEL

When eddy currents are induced parallel to the surface in a conducting material with a surface-breaking flaw, some of the current is forced to flow down the crack away from the surface and around the crack tip. This distortion of the current path leads to an eddy-current concentration at the crack tip and a depletion at the surface, compared to the exponentially decaying density with depth ("skin effect") of a nonflawed material. This phenomenon is the well-known Kahn effect. The hypothesis of the series of experiments conducted in the described work is that the resulting signal from the crack-tip concentration may be used to indicate the depth of such flaws. The primary measured signal characteristic is the arrival time of the signal of interest.

If the displacement current term in Faraday's equation is neglected, the propagation of eddy currents in a conductor is governed by the diffusion equation. Even for the relatively low conductivity ($10E6$ ohms/ohm) and high frequencies ($10E7$ Hertz), the magnitude of the displacement current is approximately 9 orders of magnitude less than the conduction current. Therefore the formation and transmission of the crack-tip signal from the Kahn effect happens on the diffusion time scale. The diffusion coefficient is

$$D = 1/(\mu\sigma)$$

where μ is the magnetic permeability and σ is the conductivity of the material. For Ti-6-4 used in the experiments, D is approximately 1.35 m/sec at room temperature. The characteristic time for a disturbance to propagate a distance d is

$$t = d / D$$

Therefore in order to resolve distances of the order of 0.25 mm, a time resolution of approximately $t = 50$ nanoseconds is required.

A theoretical model that includes the effects of a finite-length flaw is being developed. It is discussed in a companion paper in these Proceedings [6]. Preliminary results confirm a flaw depth effect, and suggest that an effective way to observe this effect is to measure the rate of decay of the receiver signal. However, at present the model cannot address the question of the relative strength of the crack tip and near-surface signals. Experiments were designed, therefore, to measure crack-tip effects.

EXPERIMENTAL APPROACH

In order to enhance the depth information, we have attempted to take advantage of the time-domain nature of the signal by separating in time the depth information from the surface-flaw information and no-flaw signal. That is, if signal transmission could be reduced before the flaw

depth signal arrives, then the depth-measurement sensitivity could be enhanced.

One possible current pulse shape is a ramp. In fact, Hendrickson and Hansen [13] have suggested this as a way to generate deeply penetrating eddy currents, then to receive signals from their decay. The difficulty of this approach is that it is necessary to stop the current flow in the excitor coil in a shorter time than the signal arrival time expected for small flaws (tens of nanoseconds in titanium). The reason is that the coil, if made capable of supplying a large signal, must have substantial inductance (of the order of 1 microhenry). A resistance of 0.01 ohm is required to passively remove approximately 2/3 of the current in 10 nanoseconds. This is a factor of 10 less than typical coil resistances, and ignores cable and winding capacitance. Alternatively, a back voltage could be applied to the probe; but the magnitude of this voltage is inversely proportional to the decay time desired. In other words, if the desired decay time is one tenth of the rise time, then the decay portion applied voltage must be 10 times the rise portion voltage. This operation mode would require the use of fewer turns of heavily insulated wire, thereby reducing the transmitted power.

The selected approach for this project is to use the waveform shown in Figure 1. When the current reaches the top of the ramp, it is held constant for a time long enough to take the desired measurements. The de-energizing of the probe can then take place at a moderate rate with a low voltage after the measurement is taken. The voltage induced in the test material according to Faraday's Law is, however, proportional to the rate of change of current in the transmitter; and decays in the time that it takes to change the probe current from a ramp to a constant value. It is this time that needs to be kept short.

BREADBOARD DEVELOPMENT

The breadboard system used for the PEC experiments and shown schematically in Figure 2 consists of the following items: (1) Texas Instruments Model 6613 pulse generator, (2) Voltage-to-current pulse amplifier, (3) Hewlett-Packard Model 9826 computer with graphics printer, (4) Tektronix Model 7854 digital oscilloscope, (5) Princeton Applied Research Model 115 wideband amplifier, and (6) Mechanical scanning system with a digital readout of position in one axis.

The pulse generator provides continuously variable pulse risetime, falltime, and duration, with each parameter independently adjustable from 10 nanoseconds up. This generator creates the voltage waveform that is fed to the pulse amplifier. The pulse amplifier, designed for these experiments, maintains the current output in close shape to the voltage input by the use of an internal feedback network. It is a wideband amplifier capable of delivering 2.5 amperes into an inductive load between 0 and 100 amperes.

The received signal is amplified by the PARC Model 115 wideband pre-amplifier. The 50-ohm input impedance of the preamplifier effectively dampens the receiver probe response to prevent ringing. The amplified signal is input to the digital oscilloscope, which also serves as the transient recorder/digitizer for the system. The oscilloscope is directly connected to the HP 9826 microcomputer via a standard General Purpose Interface Bus (IEEE-488). Signal averaging and smoothing is performed on acquired receiver signals in the oscilloscope.

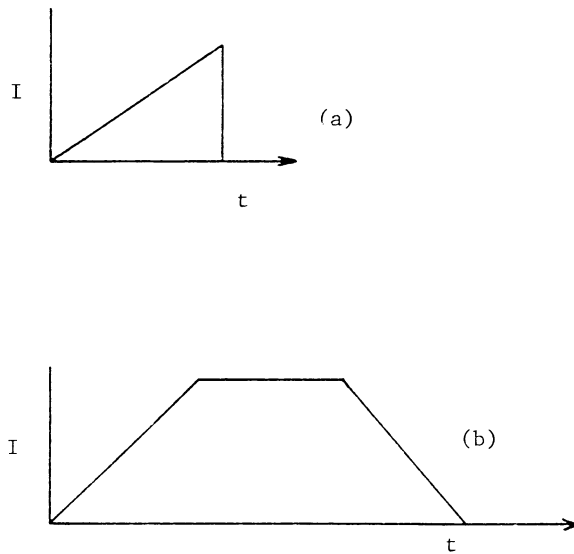


Fig. 1. Ideal Current Waveforms for Achieving Time-Domain Separation of Surface Signals and Flaw Depth Information. In case (b), a sharp change in current is not required even though signal transmission stops as quickly as in (a).

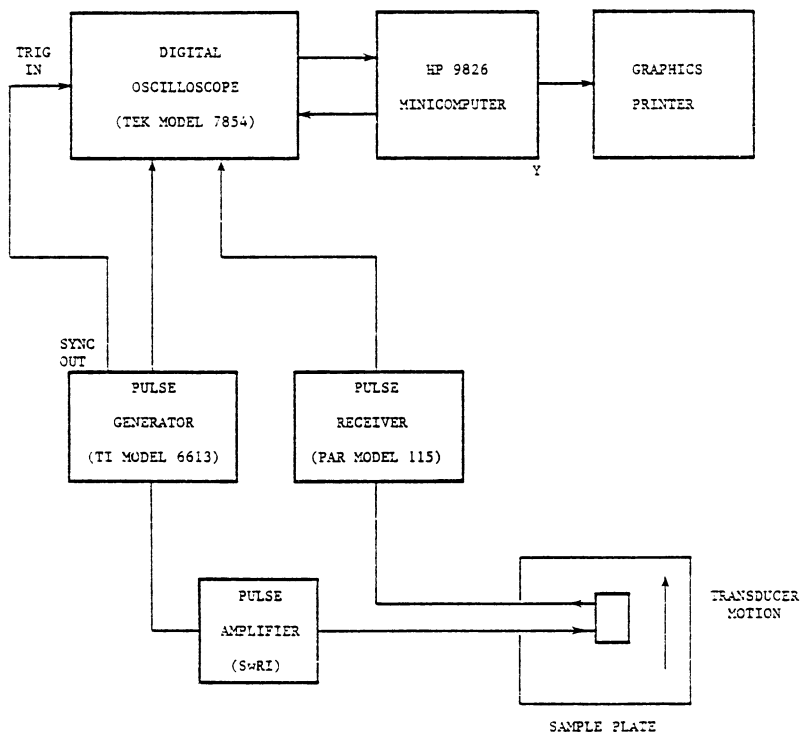


Fig. 2. Pulsed Eddy-Current Breadboard Test System. This system was constructed to allow use of monopolar pulses with variable rise/fall times and duration and with more flexible (software-controlled) feature extraction. Only the SwRI-constructed voltage-to-current pulse amplifier is not commercially available.

EXPERIMENTAL RESULTS

A series of experiments was performed on titanium test specimens with EDM notches. The probes were a single ferrite-shielded transmitter coil and absolute receiver coil.

A sample of the test results is shown in Figures 3 and 4. Figure 3 shows the receiver signal in the absence of a flaw during the ramp and constant value portions of the transmitted signal. The waveforms in Figure 4 are the difference between a flaw signal and the no-flaw signal of Figure 3. The data have not been smoothed; hence, there is substantial noise when the difference signal is formed. The difference in decay characteristics predicted by the model can be directly observed.

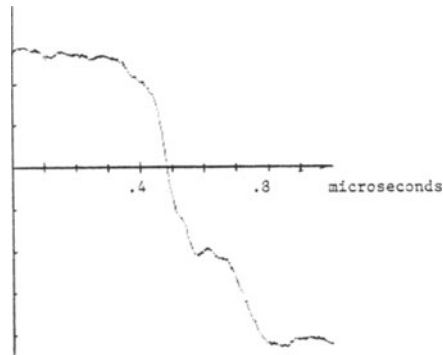


Fig. 3. The No-flaw Receiver Signal Used in a Series of Flaw Depth Measurement Tests. The amplitude drops sharply when the transmitted current becomes constant.

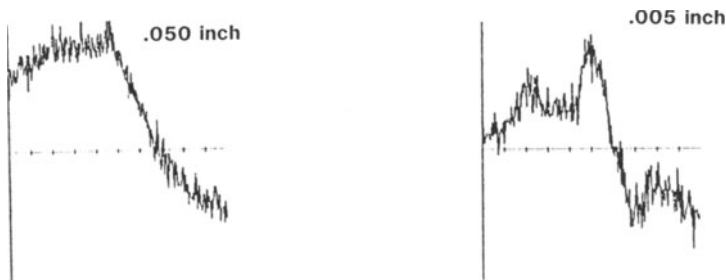


Fig. 4. Receiver Flaw Minus the No-flaw Signal for Different Depth Notches. The slope of the decaying portion of the signal decreases with increasing flaw depth, as predicted by the crack-tip model.

Figures 5 and 6 show results from experiments with a range of flaw depths and surface lengths in the titanium specimens. Figure 5 shows the maximum flaw signal amplitude as a function of flaw depth. These data were generated in the same manner as that of Figure 4; that is, by taking the difference between neighboring flaw and no-flaw receiver signals. Data for two series of flaws are shown: flaws A-D have a constant length-to-depth ratio of 2, and flaws G-J have a constant length of 0.25 mm (0.01 inch). All of the flaws have a width of 0.050 inch. Data from three different experiments show that the results are highly repeatable. It is clear that the peak amplitude of the flaw signal is a function of both depth and length in the region of interest.

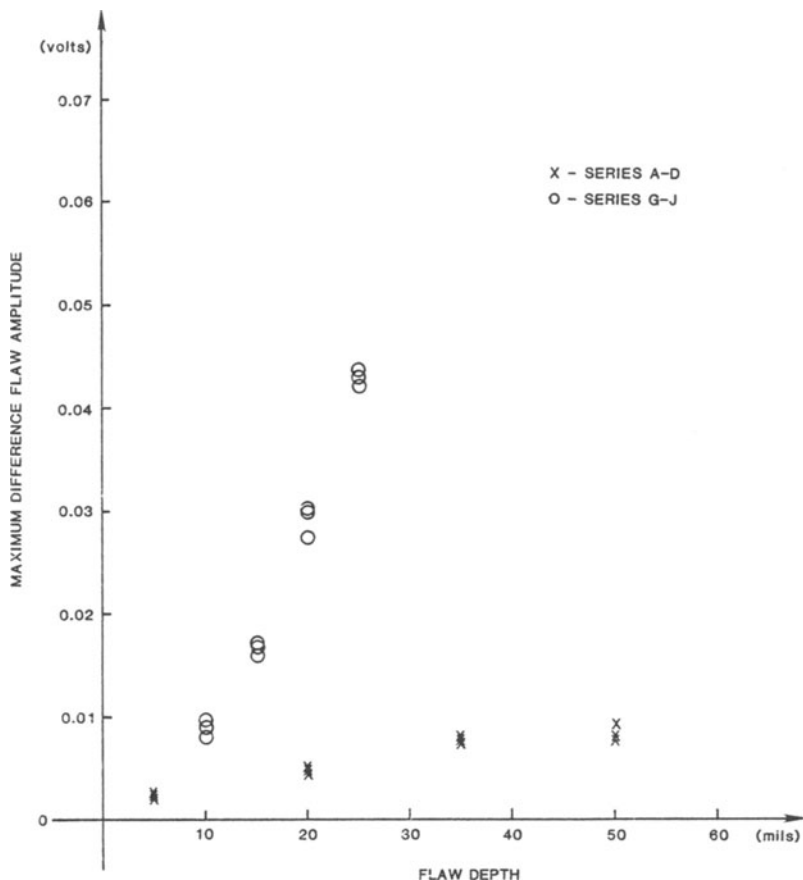


Fig. 5. Maximum Flaw Signal Amplitude as a Function of Flaw Depth. Series G-J gives a much stronger response because these flaws are longer (length-to-depth ratio of 2) compared to series A-D (length = 0.010 inch).

Figure 6 shows the time of first zero-crossing of the receiver signal from the same experiments used to generate data for Figure 5. The zero-crossing was used as a measure of the decay time of the receiver flaw signal. The maximum difference between flaws of the same depth is approximately 60 percent and occurs at the smaller depths compared to a difference of over 800 percent shown in Figure 5 at intermediate depths. The difference between the zero-crossing response of the two different flaw series appears to decrease as the flaw size becomes larger due to an anomalous increase in zero-crossing time for the G-J series at a depth of 0.010 inch. Furthermore, the scatter is significantly larger in this figure, indicating greater effects of noise on this measurement procedure. The time scale also is in the expected regime.

In conclusion, it has been demonstrated that consideration of the receiver signal decay time using the ramp pulse transmitted signal can drastically reduce the difference in response between flaws of equal depth but differing surface length. However, differences with flaw depths of less than 0.020 inch remain large. This is possibly because these flaws are short compared to the transmitter diameter (approximately 0.030 inch) and therefore due not respond as indicated in the simple physical model.

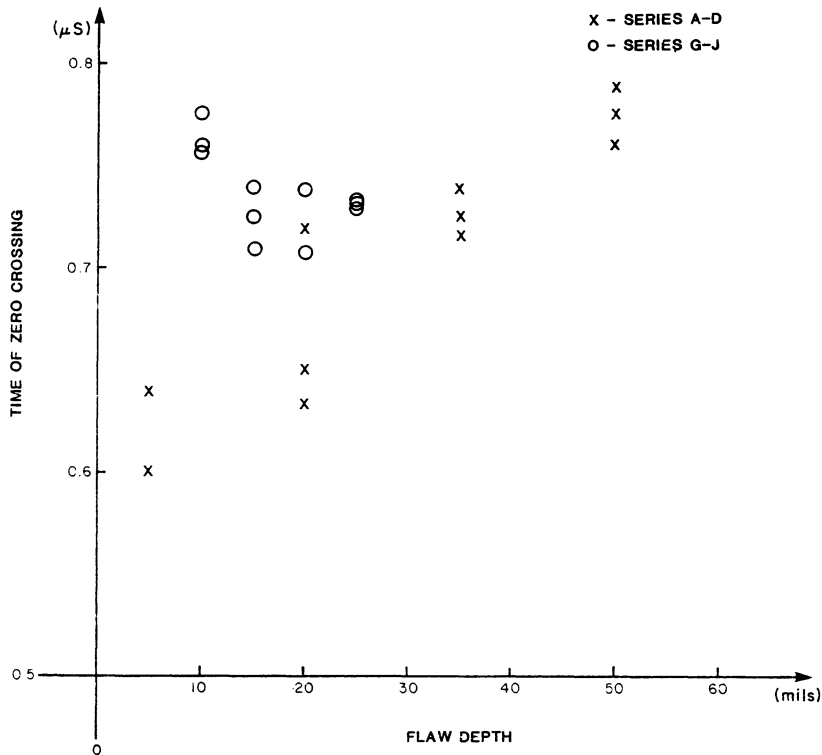


Fig. 6. Time of Receiver Flaw Signal Zero-Crossing as a Function of Flaw Depth. Flaws with equal depths give a much closer response with this measurement than the peak-amplitude measurement shown in Figure 5.

ACKNOWLEDGEMENTS

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REFERENCES

1. A. Sather, "Investigation into the Depth of Pulsed Eddy-Current Penetration," Eddy-Current Characterization of Materials and Structures, 374-386, G. Birnbaum and G. Free, Eds., ASTM STP 722.
2. D. L. Waidelich, "Reduction of Probe Spacing Effect in Pulsed Eddy Current Testing," Symposium on Nondestructive Tests in the Field of Nuclear Energy, ASTM, 1958.
3. H. L. Libby, Introduction to Electromagnetic Nondestructive Test Methods, New York: Krieger, 1979.
4. G. Wittig and H. M. Thomas, "Design of a Pulsed Eddy Current Test Equipment with Digital Signal Analysis," Eddy-Current Characterization of Materials and Structures, G. Birnbaum and G. Free, Eds., ASTM STP 722, 387-397, 1981.

5. T. H. Busse and N. S. Beyer, "Pulsed Eddy Current Inspection of Thin-Walled Reactor Tubing," Materials Evaluation, 28, 228, October 1970.
6. J. L. Fisher, R. E. Beissner, and J. E. Doherty, Exploratory Development on Advanced Eddy Current Coil Excitation and Signal Processing, prepared by Southwest Research Institute for Wright-Patterson Air Force Base, Ohio, Report No. AFWAL-TR-85-4025, April 1985.
7. R. E. Beissner and J. L. Fisher, "A Model of Pulsed Eddy Current Crack Detection," these Proceedings.